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Biases in Reanalysis Snowfall Found by Comparing the JULES Land Surface Model to GlobSnow

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ABSTRACT

Snow exerts a strong influence on weather and climate. Accurate representation of snow processes within models is needed to ensure accurate predictions. Snow processes are known to be a weakness of land surface models (LSMs), and studies suggest that more complex snow physics is needed to avoid early melt. In this study the European Space Agency (ESA)'s Global Snow Monitoring for Climate Research (GlobSnow) snow water equivalent and NASA's "MOD10C1" snow cover products are used to assess the accuracy of snow processes within the Joint U.K. Land Environment Simulator (JULES). JULES is run "offline" from a general circulation model and so is driven by meteorological reanalysis datasets: "Princeton," Water and Global Change–Global Precipitation Climatology Centre (WATCH–GPCC), and WATCH–Climatic Research Unit (CRU). This reveals that when the model achieves the correct peak accumulation, snow does not melt early. However, generally snow does melt early because peak accumulation is too low. Examination of the meteorological reanalysis data shows that not enough snow falls to achieve observed peak accumulations. Thus, the earlier studies' conclusions may be as a result of weaknesses in the driving data, rather than in model snow processes. These reanalysis products "bias correct" precipitation using observed gauge data with an undercatch correction, overriding the benefit of any other datasets used in their creation. This paper argues that using gauge data to bias-correct reanalysis data is not appropriate for snow-affected regions during winter and can lead to confusion when evaluating model processes.

1. Introduction

Snow is a vital component of land surface models (LSMs). It is the largest transient feature of the land surface (Yang et al. 2001) and has a dramatic effect upon the albedo and moisture and heat fluxes between the land and the atmosphere, exerting a strong influence on weather and climate (Gong et al. 2004). As the

earth's climate changes in terms of temperature and precipitation, snow cover is likely to change, feeding back in to the climate. Therefore, it is vital that weather and climate models accurately represent snow processes—in particular, how snow melts under different conditions.

This study focuses on the Joint U.K. Land Environment Simulator (JULES; Best et al. 2011; Clark et al. 2011). This is the land surface component of the Met Office general circulation models and is used in operational weather forecasting and long-term climate predictions (Solomon et al. 2007). Previous studies suggest that JULES melts snow too early (Blyth et al. 2010; Wiltshire 2006) and that a more complex representation

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is needed (Liston 2004; Solomon et al. 2007). However, these studies did not evaluate the snow mass [also known as snow water equivalent (SWE)] accumulated because of the uncertainty in SWE products (Clifford 2010; Déry et al. 2005; Kuchment et al. 2010). Since these studies, the European Space Agency (ESA) Global Snow Monitoring for Climate Research (GlobSnow) SWE product has been released (Takala et al. 2011) and a previous study by this group suggests that it gives a much more accurate estimate of peak SWE than previous products (Hancock et al. 2013).

This paper uses the new product along with other measures to evaluate JULES's representation of snow and the meteorological reanalysis data used to drive JULES.

2. Tools and datasets

a. Land surface model

JULES is a community LSM, originally developed by the Met Office. A range of processes are represented as physically realistically as possible (Best et al. 2011; Clark et al. 2011). The snow processes are described in detail in Best et al. (2011), but the important features are repeated below. For this study, JULES, version 3.0, was used. The snow processes are identical to the latest version (version 3.2).

JULES has two snow model options, a simple single-layer model or a newer, more physically realistic multilayer model. The multilayer model was used in the present study. A maximum number of layers and minimum layer thickness are specified—as snow depth changes, the lowest layer thickness is altered until it exceeds twice the minimum thickness (at which point it is split into two) or drops below the minimum (at which point it is joined with the bottom layer). Each layer is described by a thickness, temperature, density, ice content, and liquid water content. These parameters control the conductance and heat capacity of each layer. Over time, the density of each layer is changed, liquid water is formed, percolated down and refrozen, sublimation occurs, and the albedo is decreased via a snow grain size. In evergreen forest areas, snow is intercepted, giving a canopy and ground snow store, leading to increased sublimation.

Some argue that as well as vertical heterogeneity, horizontal heterogeneity across a grid box is needed (Liston 2004), which is not currently in JULES. This allows snow-covered and snow-free areas within a single grid box, leading to realistic albedos and soil insulation. This has been shown to delay snowmelt and soil temperature, and leads to more realistic runoff values (Wiltshire 2006). The present project aimed to implement

this additional process using earth observation (EO) data.

1) METEOROLOGICAL DRIVING DATA

When run offline JULES requires meteorological driving data. The required variables are incoming shortwave radiation, incoming longwave radiation, air temperature, precipitation (either total or separate rain and snowfall), air pressure, wind speed, and specific humidity. These can be provided at a single point by weather stations, but in this study global gridded reanalysis data were used.

Reanalysis data are a combination of general circulation model (GCM) runs with assimilated ground measurements to reduce any bias. This effectively fills in the gaps between weather stations. For this study, three reanalysis products were used: the “Princeton” dataset (Sheffield et al. 2006) and two versions of the Water and Global Change (WATCH) dataset (Weedon et al. 2010)—one using precipitation from the Climatic Research Unit (CRU) dataset, hereafter referred to as WATCH-CRU, and the other using precipitation from the Global Precipitation Climatology Centre (GPCC) dataset, hereafter referred to as WATCH-GPCC. These datasets give each variable every 3 h (some variables require interpolation from 6 h). Princeton covers the period 1948–2008 at 1° resolution. WATCH-GPCC and WATCH-CRU cover the period 1901–2002 at ½° resolution.

For this study, the most important variable is precipitation, as that drives snow accumulation. In Princeton that uses the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) model runs, no direct observations of precipitation or snow depth are used; the precipitation estimates come entirely from the weather model (constrained by atmospheric observations) (Kalnay et al. 1996). In WATCH that uses the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) model runs, snow-depth measurements from synoptic weather stations are assimilated but not used to correct modeled precipitation values (Uppala et al. 2005). In both products the precipitation is then bias corrected by matching monthly means to observed gauge data [either CRU (New et al. 1999) or GPCC (Schneider et al. 2008)]. An attempt is made to account for undercatch using correction factors derived during the World Meteorological Organization's Solid Precipitation Measurement Intercomparison (Adam and Lettenmaier 2003; Sheffield et al. 2006).

The Princeton dataset then provides this total precipitation (rain and snow) to the LSM, which uses a temperature threshold (set at 274 K here) to partition

between snow and rain. WATCH attempts to provide separate estimates of rain and snowfall by partitioning based on CRU observations (Weedon et al. 2010).

2) ADDITIONAL DATASETS

As well as meteorological data, JULES requires the fractional cover of each land cover type; this was obtained from the ECOCLIMAP database (Masson et al. 2003). JULES also requires soil hydraulic properties and albedo, and this was obtained from Dharssi et al. (2009).

b. Earth observation data

To evaluate JULES's ability to model snowmelt, estimates are required of peak seasonal SWE and the last day of continuous snow cover (snow end date). These are both available globally from remote sensing data. It would be useful also to have a measure of the melt rate of snow (SWE over time), but this is less reliably measured by remote sensing and so was not used in this study.

1) SWE

Three global SWE products are readily available: National Aeronautics and Space Administration/Japan Aerospace Exploration Agency (NASA/JAXA)'s Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E)/*Aqua* Daily Level-3 (L3) Global Snow Water Equivalent Equal-Area Scalable Earth (EASE)-Grid (AE_DySno; Tedesco et al. 2004); National Snow and Ice Data Center (NSIDC)'s Global EASE-Grid 8-day Blended Special Sensor Microwave Imager (SSM/I) and Moderate Resolution Imaging Spectroradiometer (MODIS) Snow Cover (NSIDC-0321; Brodzik et al. 2007); and ESA's GlobSnow SWE, version 1.3 (Takala et al. 2011). All three use passive microwave data from either NASA/JAXA and National Oceanic and Atmospheric Administration (NOAA) AMSR-E, SSM/I, or Scanning Multichannel Microwave Radiometer (SMMR) spaceborne instruments. Previous studies have revealed limitations and artifacts in both AMSR-E and SSM/I products (Clifford 2010; Hancock et al. 2013). An earlier study by this group (Hancock et al. 2013) found that AMSR-E saturated around 100-mm SWE, showed spurious spikes as snowmelt started, and gave much larger estimates in very cold air temperatures. These last two issues are due to changes in crystal structure that are not accounted for in the inversion. As with AMSR-E, the SSM/I product showed the same saturation and overestimate of SWE because of cold air along with additional large overestimates in forested areas because of an inappropriate vegetation correction. Thus, the peak annual SWE

values are considered unreliable and we suggest that they are unsuitable for estimating the peak annual SWE value, even when averaged over time and space.

ESA's newer GlobSnow product overcomes these issues by combining satellite data with ground measurements of snow depth. GlobSnow has a 25-km resolution and extends from 1979 to the present day with daily SWE estimates including uncertainties, although with some gaps for the early sensors (SMMR before 1987). As ground stations may not be representative of snow depth across complex topography, 25-km pixels with elevation ranges greater than 1 km are masked out as unreliable (Takala et al. 2011). Analysis was only carried out at sites with unmasked GlobSnow estimates. For more details on GlobSnow, refer to Takala et al. (2011).

GlobSnow still has a number of issues—in particular, it tends to miss the start of the snow season because of its dry snow flag (Hall et al. 2002), it struggles with SWE > 150 mm (Takala et al. 2011) and, because of its reliance on ground data, the SWE values can jump, as different weather stations contribute to the final estimate (Hancock et al. 2013). In this study we concentrate on snowmelt, so missing the start of the season is not an issue. We note that for SWE above 150 mm, GlobSnow values may be underestimates of the truth. The jumps in SWE are more problematic, with no way to know which side of the jump is the correct SWE value (and whether it is an over- or underestimate); however, these are infrequent, only occurring in around 1% of snow seasons (Hancock et al. 2013), and so we proceeded, accepting that a small fraction of GlobSnow SWE estimates may be spurious.

While there are other techniques for producing global SWE estimates (Frappart et al. 2006), these rely on the very LSMs this study aims to test, and so they were not used.

2) SNOW DATES

Estimates of snow start and end dates are a particular weakness of the GlobSnow SWE product (Hancock et al. 2013) and so we will not rely on them here. There are a number of global snow-covered area (SCA) products available (measuring the presence or absence of snow, but not the amount of snow) from which the snow end date may be retrieved.

A previous study by this group (Hancock et al. 2013) compared the MODIS/*Terra* Snow Cover Daily Level-3 (L3) Global 0.05° (0.05Deg) Climate Modeling Grid (CMG) (Hall et al. 2006) and the MODIS-SSM/I-blended product, NSIDC-0321 (Brodzik et al. 2007), hereafter referred to as the MOD10C1 and MODIS-SSM/I SCA products, respectively. This revealed that the 8-day-resolution MODIS-SSM/I SCA product

could give very different snow date estimates compared to the daily MOD10C1 SCA product because of short melt and new fall events. Therefore, in this study, the highest-temporal-resolution product available, MOD10C1, was used to avoid bias with the sub-daily JULES runs.

MOD10C1 uses the normalized difference snow index (NDSI), the ratio of the difference between the visible and infrared reflectances and the sum of the two (Salomonson and Appel 2004). This was compared to Landsat data to set an NDSI threshold to determine whether a 500-m MODIS pixel is snow covered or snow free. In MOD10C1 this is aggregated to give a fractional SCA over 0.05° . Hall and Riggs (2007) report an accuracy compared to ground observations of 93%, although over evergreen forest this decreases to 80% because of shadowing (Painter et al. 2009; Frei et al. 2012). There is no SCA product available that will not suffer from this issue and so MOD10C1 was used here, accepting reduced accuracy over evergreen forest.

MOD10C1 extends from 2000 to the present day at 0.05° spatial resolution and daily temporal resolution. As MODIS is a passive optical instrument, there are gaps in the data because of cloud cover and the lack of daylight during the Arctic winter.

3. Experiments

All datasets were aggregated at the coarsest resolution (Princeton at 1°) by taking the simple mean, and all subsequent analysis compared these values. GlobSnow and MOD10C1 pixels were assigned to a single 1° pixel, ignoring any partial overlap. For JULES driven by WATCH, the driving variables were averaged up to 1° and a single JULES run was performed. JULES was run with 3-h time steps. A maximum of eight snow layers were used with 10-cm-layer thickness. Freshly fallen snow was given a density of 100 kg m^{-2} . All other parameters were left as the default values unless driven by the soil or land surface maps.

a. Preliminary analysis

Initially, time series of JULES SWE, GlobSnow SWE, and MOD10C1 SCA were generated for 1381 pixels spread around the Northern Hemisphere (see Fig. 2), chosen to be representative of the global snow-affected areas in terms of latitude, longitude, elevation, topographic variation, and peak annual SWE, to allow a visual examination of the behavior of JULES relative to GlobSnow and MOD10C1. Each year of overlapping data was plotted separately so as not to hide any effects in a climatology. GlobSnow SWE was smoothed by a 5-day median filter to make the general behavior more apparent.

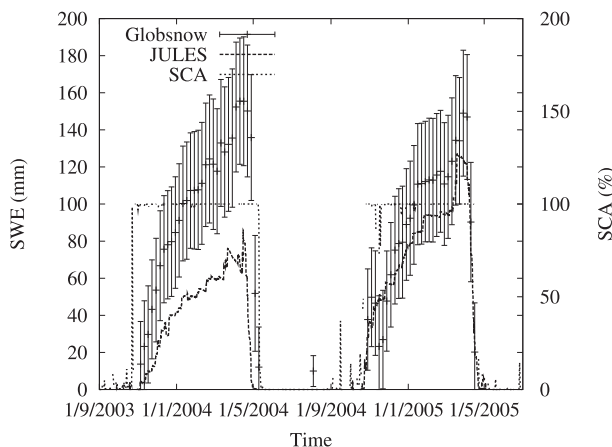


FIG. 1. JULES SWE driven by Princeton, GlobSnow SWE, and MOD10C1 SCA for 60.5°N , 65.5°E . Error bars are from the the GlobSnow inversion uncertainty.

PRELIMINARY RESULTS

Figure 1 shows two years illustrating the most commonly observed behavior. It can be seen that in the 2003/04 season, JULES melts the snow 1–2 weeks earlier than MOD10C1 and GlobSnow suggest, but the peak accumulation by JULES was only 50% of that given by GlobSnow. As there was not enough snow accumulated, we would expect it to melt early, even if JULES predicted the correct melt rate.

In the 2004/05 season, the JULES peak accumulation is within 5% of the GlobSnow estimate and the JULES snow end date is exactly the same as both MOD10C1 and GlobSnow. These patterns of behavior were apparent in all years and pixels examined when driven by Princeton, WATCH-GPCC, and WATCH-CRU. Hence, it is likely that the observed early melt of JULES is as a result of insufficient snow accumulating, rather than to excessive melt rates because of simplified model physics. Therefore, we proceeded to perform a quantitative analysis of these results and to suggest explanations of the features shown in Fig. 1.

b. Sites

As the peak SWE and end date extraction methods used are automatic, much larger areas can be easily analyzed, rather than the limited subset initially examined. The four snow-affected basins used by Blyth et al. (2010)—the Mackenzie, Lena, Ob, and Yenisey (Fig. 2)—as well as every land pixel north of 50°N with valid GlobSnow values were examined.

c. Metrics

For JULES and GlobSnow, peak accumulation was taken as the highest mean SWE in any 10-day period

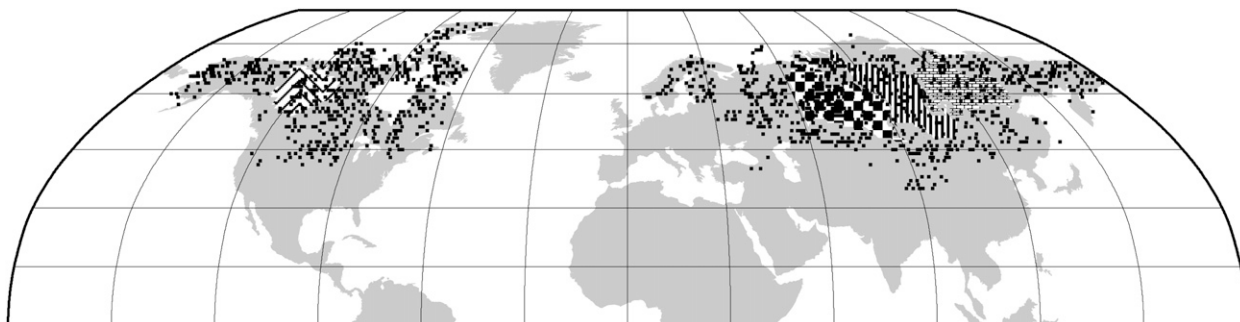


FIG. 2. Location of river basins used: from west to east, the Mackenzie, Ob, Yenisey, and Lena. Dots show the 1381 globally representative pixels.

between 1 July and the following 1 July in two consecutive years. The 10-day window was used to avoid noise in GlobSnow.

To determine the snow end date, MOD10C1 data were smoothed using a 5-day median filter to remove noise. The end date was taken as the first day after 1 February (a day we can be confident was snow covered) with SCA less than 3%. For JULES, the end date was taken as the first day after 1 February on which the SWE fell below a threshold (set to 1 mm to avoid rounding issues). Areas with missing data because of Arctic winter (unlikely in the melt season) or clouds were not used in the analysis.

4. Results and discussion

a. JULES

Figure 3 shows the difference between the JULES and MOD10C1 snow end dates plotted against the difference between the JULES and GlobSnow peak annual SWE for the Mackenzie and Lena basins and driven by each reanalysis dataset. Data from the other basins exhibited similar patterns. Each point represents a single year at a single pixel. The black cross shows the origin. Points above the horizontal line have JULES melting the snow too late compared to MOD10C1 and points below melt too early. Points to the left of the vertical line have too little snow accumulating in JULES compared to GlobSnow and points to the right have too much.

This quite clearly shows that JULES does melt snow too early on average, but also that not enough snow is accumulating across all these basins. The graphs for the Ob, Yenisey, and all points north of 50°N show the same behavior; although for the latter, because of the number of points (and some outliers), this is less clear. This strongly suggests that the early melt observed in JULES is a result of insufficient snow accumulation.

There are two possible reasons for this: 1) that there is not enough snow falling and 2) that the falling snow is ablating too readily.

b. Snowfall

The cumulative snowfall within a snow season was calculated and compared to GlobSnow peak SWE. If not enough snow is falling to give the observed peak SWE, then it is very likely that the early snowmelt is a result of insufficient snowfall rather than excessive early winter ablation.

The date after which snow settles and the date of peak accumulation were calculated from JULES runs. While admittedly this may introduce some error, it avoids the noise and gaps in GlobSnow and MOD10C1 data. From Fig. 1 it can be seen that the JULES snow start date and date of peak accumulation agreed well with MOD10C1 and GlobSnow; furthermore, this was the case for all 1381 pixels examined.

Figure 4 shows histograms of the difference between GlobSnow peak SWE and cumulative snowfall from the three driving products for all land points north of 50° with valid GlobSnow values. Some pixels show very large snowfall values compared to GlobSnow, leading to the long negative tails in all histograms. These are infrequent, but their large size skews the mean and standard deviation of the difference, apparently making the difference between cumulative snowfall and GlobSnow peak SWE statistically insignificant. These outliers were closely examined and found to be due to one of four causes: 1) missing GlobSnow data, 2) warm areas with significant midwinter melt, 3) jumps in GlobSnow, or 4) areas with SWE over 150 mm where GlobSnow is likely to saturate. We can be confident that they are erroneous and can use the median—rather than the mean—to quantify the average difference.

Table 1 shows the median and first and third quartile values for the data in Fig. 4. This suggests that all three

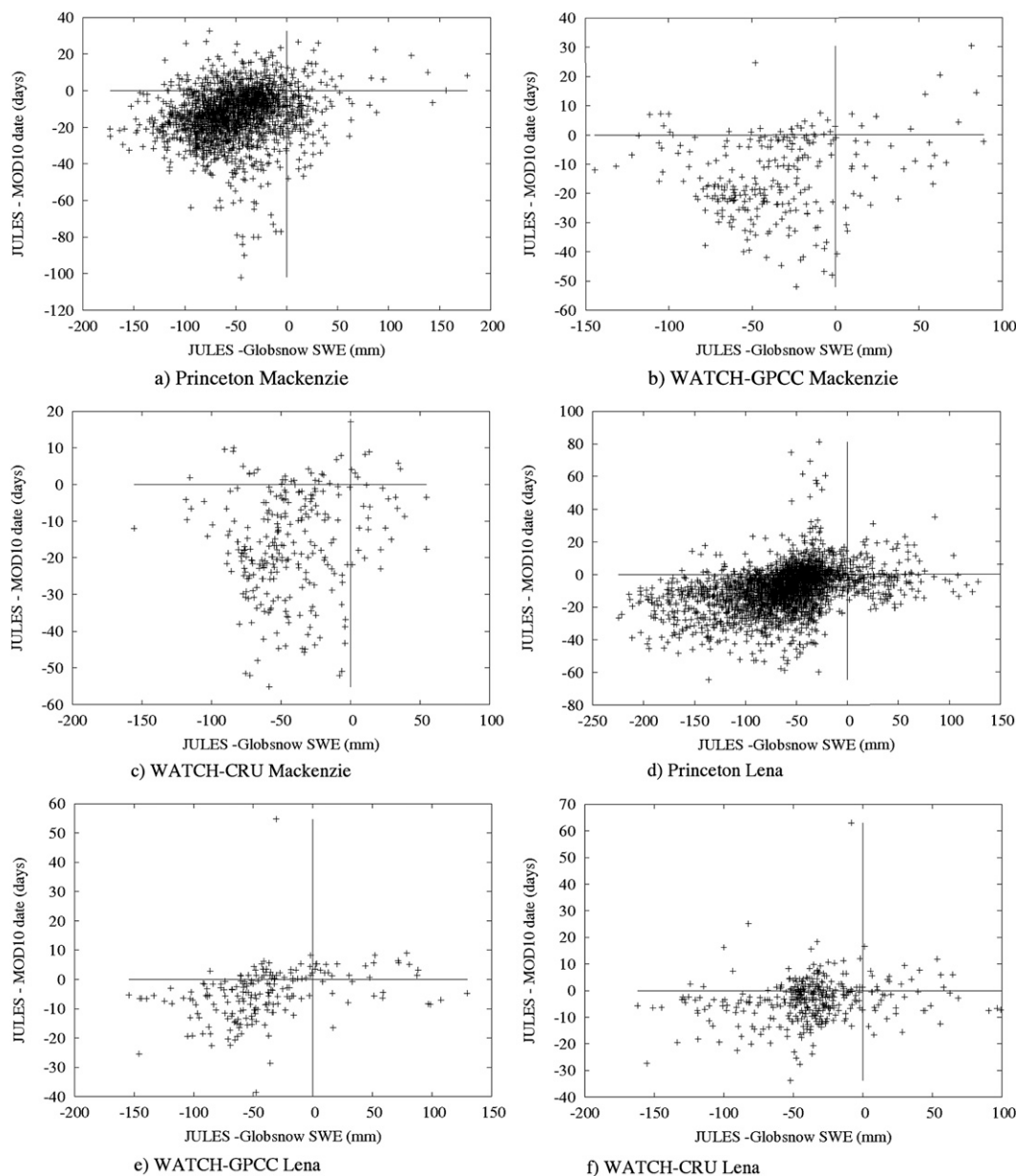


FIG. 3. Scatterplots of JULES melt date error against JULES peak accumulation error. Each point represents the results for a single year at a single 1° pixel.

driving datasets have insufficient winter precipitation to give the observed peak accumulations. Therefore, it is not surprising that JULES melts snow too early, as there is not enough snow there in the first place. To rule out the possibility of the lack of snowfall because of too low a snow–rain temperature threshold (274 K here, although only applicable to Princeton) the analysis was repeated, considering all precipitation during the continuous snow period (calculated from JULES) to fall as snow. Even when all precipitation within the start and

end of the accumulation period (using a JULES run with a threshold of 274 K) falls as snow, the observed peak SWE is not reached; therefore, this is not a temperature threshold issue, as long as the accumulation start and end dates are correct.

Interestingly, during the reanalysis data generation, the rain gauge bias correction decreased the GCM's global precipitation [−8.8%, or −1.7% with undercatch correction, for the global 1948–2000 average; Sheffield et al. (2006)]; therefore, it may be the case that the

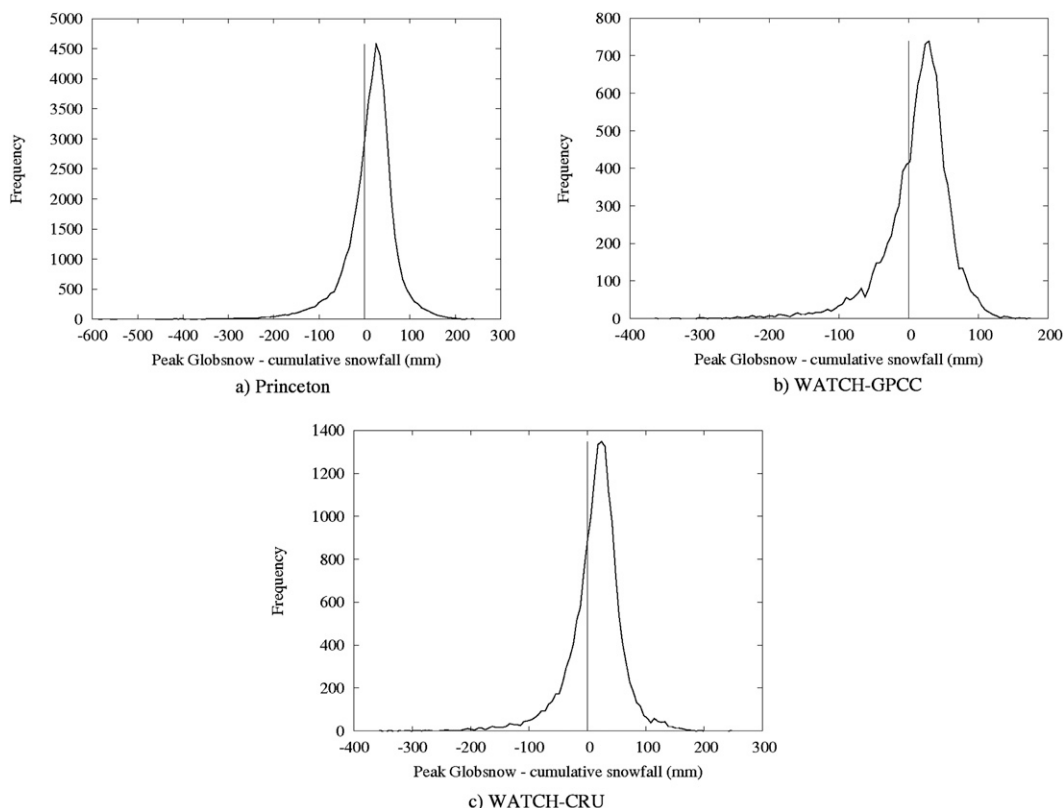


FIG. 4. Histograms of the difference between GlobSnow and cumulative snowfalls for all land points north of 50°N with valid GlobSnow values.

GCMs are correctly estimating precipitation, but that this has been overridden by the rain gauge “bias correction.” The differences between GCM and gauge data were not given separated by region and season, so it is not possible to quantify the difference for snow alone. A regional and seasonal analysis would be needed to determine the bias between GCMs and precipitation gauges for snow.

Measuring winter precipitation is notoriously difficult (Groisman et al. 1991; Fuchs et al. 2001), and we suggest that it might be more useful to correct winter precipitation using snow-depth measurements rather than gauge data.

5. Conclusions

We have shown that, while JULES does melt snow too early compared to EO data when driven by Princeton, WATCH-CRU, or WATCH-GPCC datasets, agreeing with earlier studies (Blyth et al. 2010; Wiltshire 2006), this is a result of insufficient accumulation. We suggest that it is impossible to use these reanalysis products to assess the snowmelt physics, in JULES or other LSMs, unless the correct peak SWE accumulation is reached.

Initial results from this analysis were used to scale snowfall by Finney et al. (2012), leading to much improved estimates of total runoff from the Ob, Yenisey, and Lena catchments. That study also introduced a partially permeable frozen soil model to JULES that improved the timing of peak runoff but could not produce the observed runoff quantity without first scaling the snowfall. Thus, two independent studies have found insufficient accumulation in northern river basins, suggesting that this is a problem that needs addressing before we can reliably use these reanalysis datasets to test the absolute performance (in terms of snow end date, runoff quantity, etc.) of LSMs.

These results suggest that it may be more appropriate to scale winter precipitation by observed snow-depth

TABLE 1. Median and interquartile differences between peak GlobSnow SWE and annual cumulative snowfall.

Dataset	Median (mm)	First quartile (mm)	Third quartile (mm)
Princeton	21.7	−6.5	43.7
WATCH-GPCC	20.5	−7.6	40.7
WATCH-CRU	19.3	−4.8	38.9

rather than relying on the accuracy of precipitation gauges, even when corrected for undercatch because of wind, as ERA-40 does before the WATCH gauge correction is applied (Uppala et al. 2005). It may even be possible to assimilate GlobSnow into GCMs to create more accurate snowfall predictions, but a thorough understanding of GlobSnow's accuracy is needed before this can be done—in particular, the jumps—as ground station changes would confuse an assimilation scheme.

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